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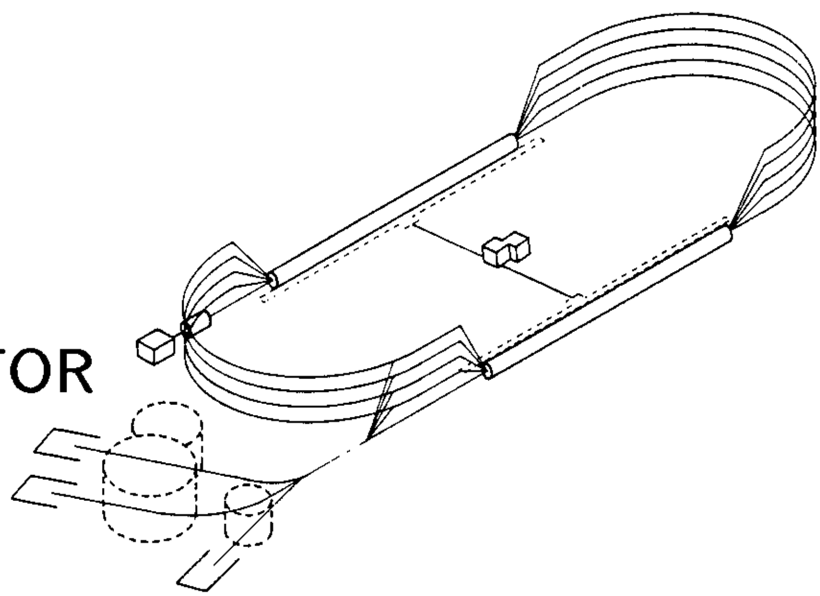

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Abstract

Construction of the Continuous Electron Beam Accelerator Facility recirculating linac represents the largest scale application of superconducting rf (SRF) technology to date. Over 250 of the eventual 338 SRF 1497 MHz cavities have been assembled into hermetic pairs and completed rf testing at 2.0 K. Among these, 52% demonstrated usable gradients greater than 10 MV/m.

Although the rf performance characteristics well exceed the CEBAF baseline requirements of $Q_0 = 2.4 \times 10^9$ at 5 MV/m, the usual limiting phenomena are encountered: field emission, quenching, Q-switching, and occasional multipacting. An analysis of the occurrence conditions and severity of these phenomena during production cavity testing is presented. The frequency with which performance is limited by quenching suggests that additional material advances may be required for applications which require the reliable achievement of accelerating gradients of more than 15 MV/m. The distributions of frequency and Q for a higher-order mode are also presented.

I. INTRODUCTION

The Continuous Electron Beam Accelerator Facility in Newport News, Virginia, USA is presently constructing a recirculating linac designed to produce a low-emittance electron beam with a current of 200 µA and energies upwards of 4 GeV for fundamental experimental studies in nuclear physics. Currents in excess of 260 µA have been achieved from the 45 MeV injector. Low-current precommissioning activities have produced a 245 MeV beam with the desired emittance characteristics.[1] The performance of the SRF accelerating cavities exceeds design requirements.

As of 1 May 1993, 127 cavity pair assemblies have completed testing and 28 1/4 cryomodules have been installed in the tunnel. Construction and installation will continue through December 1993. Nuclear physics experiments are to begin in 1994.

II. CEBAF SRF CAVITIES

In 1989 CEBAF placed a contract with Siemens for the manufacture of 360 5-cell niobium cavities according to a design developed at Cornell University. These cavities have been fabricated in accordance with CEBAF's "Statement of Work" using high-purity niobium of RRR ≥ 250 for the cavity cells and reactor grade niobium for beam pipes, waveguide couplers and flanges. The order has been completed recently as scheduled. Experiences with mechanical features of these cavities are described in papers [2] and [3] contributed to this conference.

The cavities are tuned for a flat field profile by the vendor, but received no surface treatment except for a preliminary cleaning.[4] The chemical processing takes place at CEBAF with a material removal of ≥ 50 µm, ultrapure water rinsing assisted by ultrasonic agitation, and final solvent rinsing with ultrapure methanol or isopropanol. Two cavities are assembled into a hermetically sealed pair, the basic building block of the CEBAF acceleration system, in a class 100 cleanroom. Ceramic rf windows, higher-order-mode loads [5], high-vacuum gate valves, and rf probes are attached to the cavity openings with indium seals. The pair is evacuated in the cleanroom and is maintained under vacuum thereafter.[6] After assembly, each pair is mounted on a vertical test stand and placed in a dewar in the CEBAF Vertical Test Area (VTA). The cavities are cooled quickly through the 100 K range to avoid Q degradation, and rf testing is performed at 2.0 K. The ambient magnetic field at the cavity is reduced to ≤ 10 mG by an active coil and layers of magnetic shielding. The cavity vacuum is ≤ 10^{-6} torr prior to cooldown.

A new He desorption leak detection technique with a sensitivity of 10^{-15} std cm^3/sec has been developed to verify seal integrity at cryogenic temperatures.[7]

III. RESULTS AND DISCUSSION

A. *Cavity Performance in Pair Tests*

Typically 45 minutes per cavity is required to characterize the Q_0 and E_{acc} performance and calibrate the transmission pickup probe. In addition, measurements are made of Qs of higher-order modes (HOMs) and a resonance in the fundamental power coupler. The latter is done to assess rf dissipation in the cold ceramic window. Test results for three cavities are presented in Figure 1.

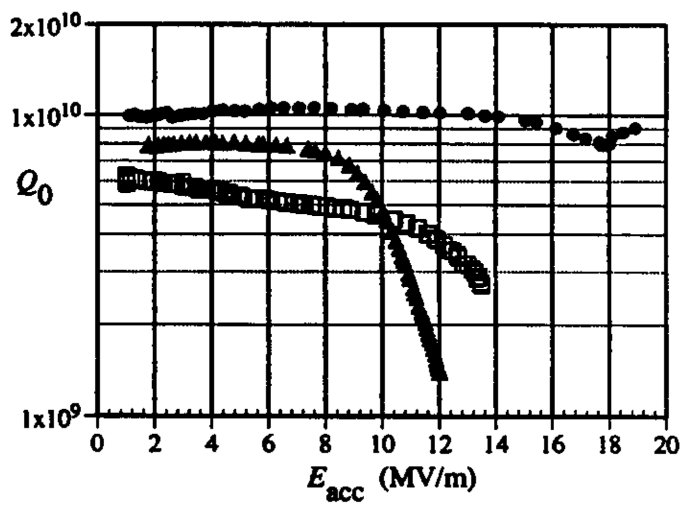

Figure 1. Typical cavity performance in vertical testing.

In the majority of cases the Q value at 2 K is ≈ 10^{10}, corresponding to a residual resistance of ≈ 15 nΩ. Lower Q values have been observed when the ambient magnetic field at the cavity during cooldown had increased due to current

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fluctuations in the coil or when insufficient amounts of material had been removed during chemical processing.

From the perspective of cavity performance alone, the "usable" accelerating gradient of a cavity has been defined as that field which is the minimum of:

$E_{acc}[Q_0 = 2.4\times10^9]$, $E_{acc}[Q_{FE}=10^{10}]$, and
$E_{acc}[\text{quench}] - 1$ MV/m.

Figure 2 presents the distribution of usable gradients of cavities which completed testing in the VTA through 1 May 1993.

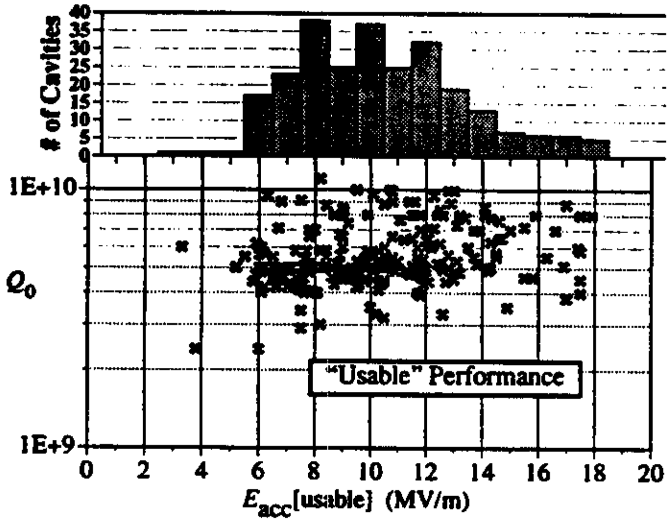

Figure 2. Cavity Q factor at maximum "usable" gradient.

These performance results were reached in initial testing of the cavities in all but 2% of the cases; a statistic is important for large-scale applications of SRF technology such as the proposed TESLA machine.

Several minutes of cw rf processing with up to 100 W critically coupled to the cavity produces 10–30% gain in performance in approximately 50% of the cavities. This rf processing normally takes place as a continuous process, until a "jump" in field level occurs. "Electronic" quenches ($\tau \leq 150$ ns) have been observed in that instance.

There have been cases where rather strong barriers were encountered below 1 MV/m. Such barriers are very unlikely to be multipacting barriers in the cavity because they would represent a very high order of multipacting. Possibly these low-field barriers are caused by some electronic processes in the variable coupler or the rf window, but this has still to be confirmed. Sometimes it has been beneficial to apply high rf power to the other members of the fundamental passband in order to process a barrier.

The incorporation into the test stands of hermetically sealed rf cable assemblies with welded dewar feedthroughs eliminated a problem with low-pressure gas discharges at standard rf connectors inside the dewar.[8]

Field emission (FE) loading is the most common performance limiting mechanism, although 104 cavities have exceeded gradients of 9 MV/m without significant FE loading. See Figure 3. The degradation of the Q value due to FE has been analyzed on the basis of the modified Fowler-Nordheim theory, and the fit parameter "field enhancement factor", β, has been extracted.[9] After processing per above, this value is observed to peak at around 200 as shown in Figure 4.

Minor Q-switches have been observed in about 2% of the

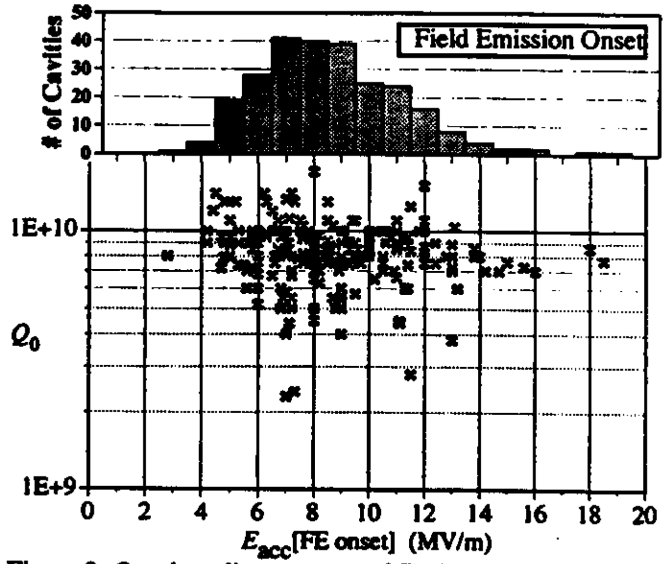

Figure 3. Q and gradient at onset of field emission loading.

cavities. Typically, a hysteretic step in Q from 9×10^9 to 6×10^9 was seen at a gradient of 3 to 7 MV/m. The Q-switches usually persist after cavity reprocessing.

It has been found that the lower of the two cavities in a vertical pair test tends to exhibit greater FE loading than the upper unless the initial cooldown conditions are controlled so that the assembly is cooled as uniformly and as quickly as possible. The enhanced field emission is attributed to locally concentrated adsorbed gas from the residual components of the cavity vacuum.

Thermal-magnetic quench has been exhibited by about half of the cavities in the last 100 qualified pairs. Among these, the average E_{acc}[quench] is 13.0 MV/m. The Q value and gradient just below quench are presented in Figure 5. In the best case the cavity tolerated a dissipated power of 55 W just prior to quench.

It should be noted that this paper addresses only the performance of CEBAF cavities during vertical testing. Detailed performance testing of cavities installed in CEBAF cryomodues is more complicated. In most cases, operational gradients are constrained by hardware protection interlocks monitoring the waveguide section between the warm and cold rf windows.[10]

B. Performance Durability

On occasion, the ceramic rf windows show leaks of less than 10^{-7} torr l/sec after cryogenic testing of the cavities. The mechanisms for these failures are not yet understood, but

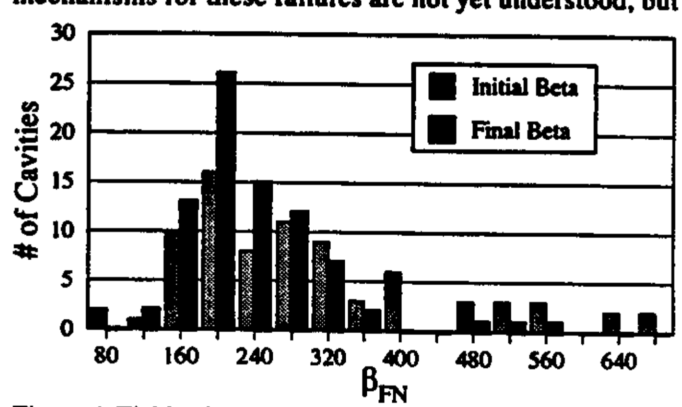

Figure 4. Field enhancement factors for FE limited cavities.

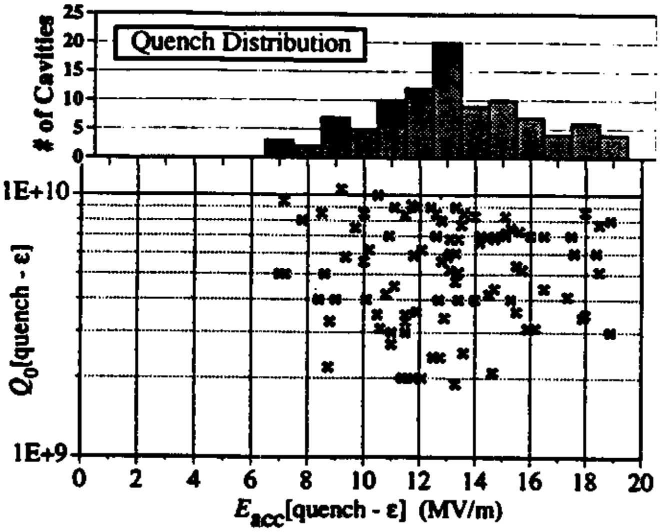

Figure 5. Cavity Q and gradient just below quench.

several investigations are underway at CEBAF.[11],[12] In such instances, the rf windows have been exchanged in the cleanroom after careful venting of the cavity pair with filtered N_2 gas. The pair was reevacuated and retested with no degradation of rf performance even on the best performing cavities with $E_{acc} \geq 16$ MV/m.

Less successful were attempts at exchanging the assemblies which interface to the helium vessel of the horizontal cryostat. In all cases where the assemblies at both ends were replaced, the cavities performed worse after the exchange than before. We attribute this to our inability to maintain a positive flow of nitrogen during the more complex exchange operation thus allowing some particulate contamination of the cavity surface.

On several occasions cavity pairs which had proceeded on through subsequent assembly into horizontal cryostats were removed and retested vertically to assess the durability of the cavity rf performance through these handling procedures. The rf performance did not degrade in those cases where the cavities received exposure only to filtered N_2 or cleanroom air.

C. HOM Measurements

Included in the vertical pair testing is the measurement of the frequency and loaded Q values of two members of the TE_{111} passband. This is used to verify the effectiveness of the HOM loads and to determine the distribution of frequencies produced by the manufacturing tolerances and cavity tuning. Figure 6 presents the results for the mode with a nominal frequency of 1980 MHz, showing quite adequate damping of this mode.

IV. CONCLUSIONS

CEBAF has completed the assembly and testing of 250 out of 338 SRF cavities. Thanks to an excellent industrial partner and stringent QA procedures, the performance of the cavities consistently exceeds CEBAF design specifications of $Q_0 = 2.4 \times 10^9$ and $E_{acc} = 5$ MV/m. In the cases where the achievable gradients were limited by thermal-magnetic breakdown, a rather large spread between 7 to 18 MV/m was observed. This suggests that the presently available high purity niobium of RRR ≥ 250 does not yet provide sufficient thermal stability to reliably support the gradients of $E_{acc} \geq 20$ MV/m needed for future linear collider applications.

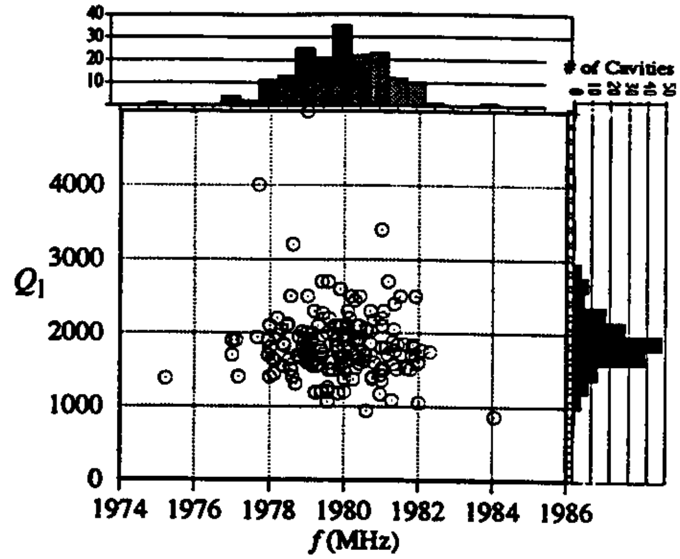

Figure 6. Distribution of frequency and loaded Q for a HOM.

V. ACKNOWLEDGEMENTS

We would like to thank all colleagues who contributed to this work, especially the members of the chemroom, assembly, and VTA teams.

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